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**AN ALGORITHM FOR COMPUTING
THE RANGE OF TRIMABLE
ANGLE OF ATTACK FOR
AIRCRAFT EXPERIENCING
EFFECTOR FAILURES**

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An Algorithm for Computing the Range of Trimable Angle of Attack for Aircraft experiencing Effector Failures

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ABSTRACT

This paper presents a method for computing the range of angle of attack for which an air vehicle can be rotationally trimmed when experiencing control effector failures. The algorithms are applied to an unpowered reentry vehicle as an example. Types of failures considered include floating effectors that do not contribute to the aerodynamic forces and moments or effectors that are locked at a given position within the effector displacement range. The algorithm can provide critical information to online trajectory generators or path planners for autonomous air vehicles.

INTRODUCTION

The algorithm presented here makes use of portion of a direct control allocation algorithm method that was previously developed by Durham [1]. The direct control allocation approach requires the computation of an Attainable Moment Set (AMS). The AMS describes a volume in the moment space. Points inside of this volume can be reached by deflecting the vehicle control surfaces in some combination. The basic idea behind direct allocation is to numerically determine an attainable moment set that will be used to solve a constrained control allocation problem. In the event that the desired moment lies outside the AMS volume, the direction of the command is preserved but clipped at the AMS boundary. Durham's algorithm for computing the AMS uses simple geometric notions to determine the boundary by computing a three dimensional geometric shape in the moment space $\vec{M} = [C_l, C_m, C_n]$, where C_l is the rolling moment coefficient, C_m is the pitching moment coefficient, and C_n is the yawing moment coefficient. A conceptual example of an AMS is shown in Figure 1 in terms of the

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moments (not coefficients). For a more detailed explanation of the calculation of an AMS, the reader is referred to references [1,2, 3].

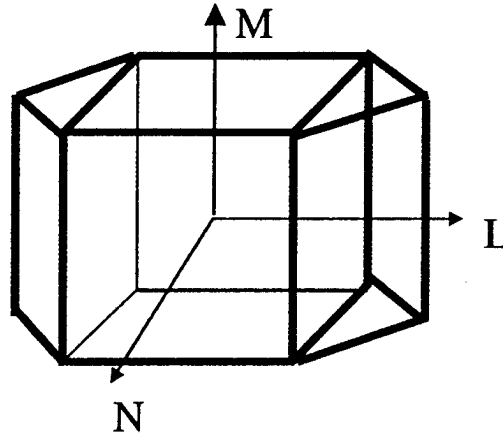


Figure 1: Attainable Moment Set (AMS) 3-D geometrical shape

Durham's algorithm is based on the assumption that the control effectors (surfaces) are individually linear in their effect throughout their ranges of motion. In other words, the algorithm assumes that the aerodynamic moments can be expressed as linear combinations of the deflections ($\vec{M} = B\vec{U}$) where $\vec{M} = [C_l, C_m, C_n]$ is the moment vector, B is the control effectiveness matrix, and \vec{U} is the control deflection vector. This assumption implies that the vehicle is already trimmed, i.e., the vehicle is stable with zero rotational motion at a given flight condition.

The idea of an AMS is useful when one is interested in computing the range of trimable angle of attack for aircraft experiencing control effector failures. It is clear that the AMS volume decreases as control surfaces fail. This reduction in volume can translate into a reduced range of flight conditions over which the vehicle can be trimmed. In order to trim at a given flight condition, the moment generated by the wing-body-propulsion (base) system must be cancelled by some combination of control effector deflections. The base moment vector changes as a function of flight condition. Untrimable conditions result when the tip of the base moment vector lies outside of the AMS volume.

Some complications arise when attempting to use Durham's AMS algorithm to compute the range of trimable angle of attack. One must consider the fact that the moments generated by the effectors are generally nonlinear functions of the control deflections, and that the vehicle may not be trimmed at certain flight conditions. Vehicle trim conditions should satisfy the following set of equations:

$$\begin{aligned} L_0(\alpha, \beta, mach) + L_\delta(\alpha, \beta, mach) \delta &= 0 \\ M_0(\alpha, \beta, mach) + M_\delta(\alpha, \beta, mach) \delta &= 0 \\ N_0(\alpha, \beta, mach) + N_\delta(\alpha, \beta, mach) \delta &= 0 \end{aligned}$$

where δ is the effector deflection, L_0 , M_0 , and N_0 are the base rolling, pitching and yawing moments respectively, L_δ , M_δ and N_δ are the control effector rolling, pitching and yawing moments respectively, and $\delta_{\min} \leq \delta \leq \delta_{\max}$.

Part of this research concentrated on extending the AMS algorithm for an untrimmed vehicle with a nonlinear aerodynamic database. An unpowered re-entry vehicle was chosen as the test platform to verify the effectiveness of the algorithm in computing trimable range of angle of attack for given effector failures. It is worth noting that this algorithm can be applied to any air-vehicle and is not limited to unpowered re-entry vehicles. The re-entry vehicle under consideration has 8 aerodynamic control surfaces, left-right body flaps, left-right inboard/outboard elevons and two rudders.

PROBLEM FORMULATION

In this section, we shall discuss the development of two separate algorithms. Both algorithms compute a range of attainable angle of attack (α) under certain effector failures. The first algorithm is a benchmark-type algorithm where we use the nonlinear aerodynamic database to compute the exact range of attainable angle of attack (α) directly from the vehicle aerodynamics. The results from this algorithm will be used as the benchmark data. The algorithm simply uses the vehicle flight conditions such as Mach number, sideslip angle, effector displacement limits (min and max), and type of effector failure(s); then computes a range of attainable angle of attack (α) by comparing the base pitching moment and the pitching moment due to effector displacements (both the minimum and maximum). That is;

$$C_{m_{MIN}} \leq C_{m_0} \leq C_{m_{MAX}}$$

Where $C_{m_{MAX}}$ and $C_{m_{MIN}}$ are the maximum and minimum pitching moments that the control effector suite is capable of generating.

A graphical representation of the above equation and discussion is presented in Figure 2 below. Under a certain effector failure, the base pitching moment (C_{m_0}) is unaffected while the minimum and maximum pitching moment bounds vary according to the type of effector failure(s). In other words, from Figure 2, the black solid line does not change due to effector failures while the red (max moment) and blue (min moment) solid lines shift depending on the type of effector failure(s).

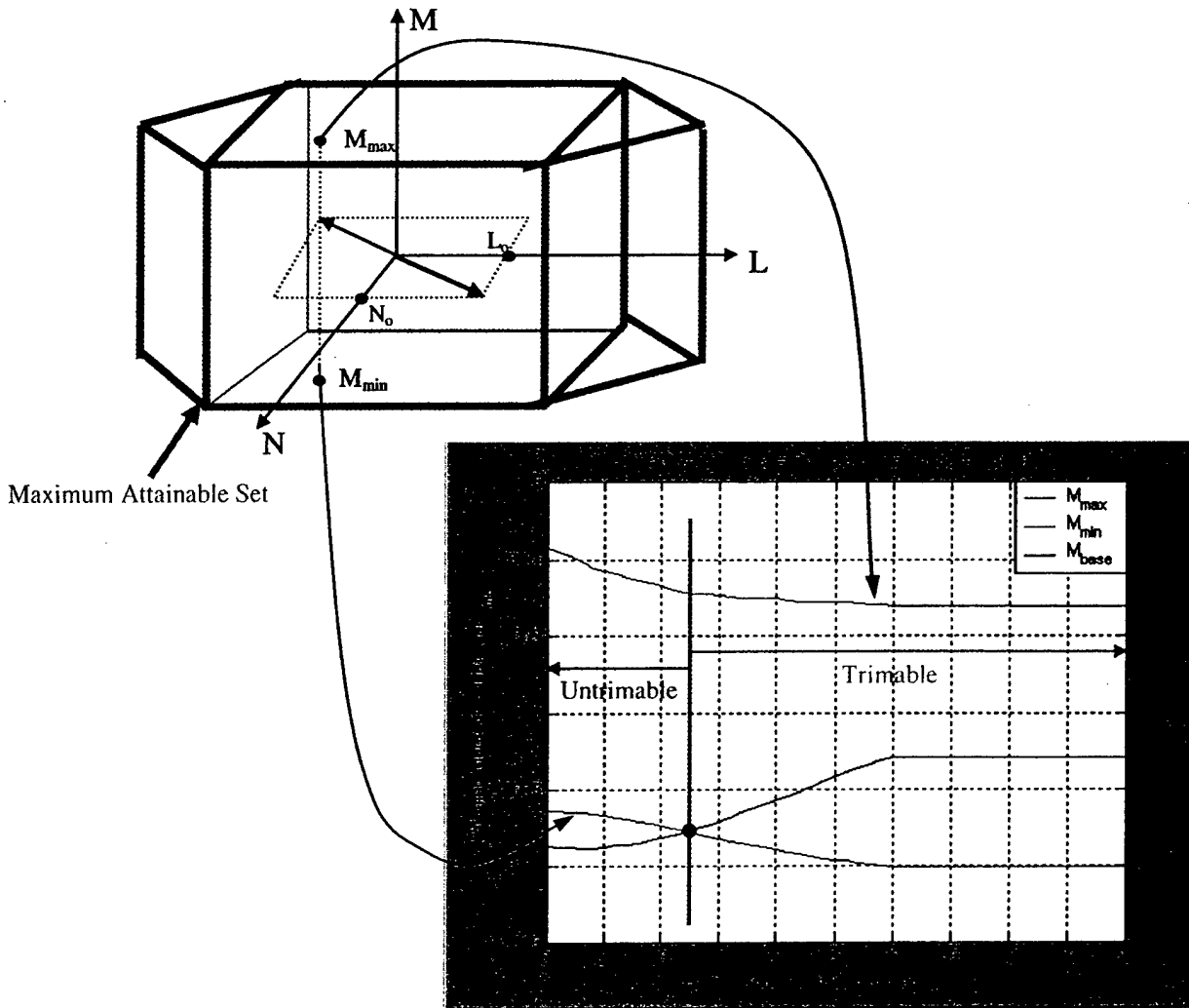


Figure 2: Moments (min,max,base) shown in 3-D moment space and equivalent 2D plot

Two additional examples are presented where the benchmark algorithm is utilized. These examples are shown in Figures 3 and 4 and graphically illustrate the range of angle of attack over which the vehicle can be trimmed under a given flight condition and effector failure(s). Figure 3 shows an example where the body flaps failed at their maximum displacement of 26 degrees. For this case, the vehicle can be trimmed over the following range of angle of attack: ($\alpha=[0\ 4]$). This is where the base pitching moment value (black line) lies between the maximum (red line) and minimum (blue line) pitching moments that can be generated by the unfailed control surfaces; respectively. The vehicle cannot be trimmed in regions where the sum of the base and failed effector pitching moments lies outside of the maximum and minimum moments that can be generated by the unfailed effectors.

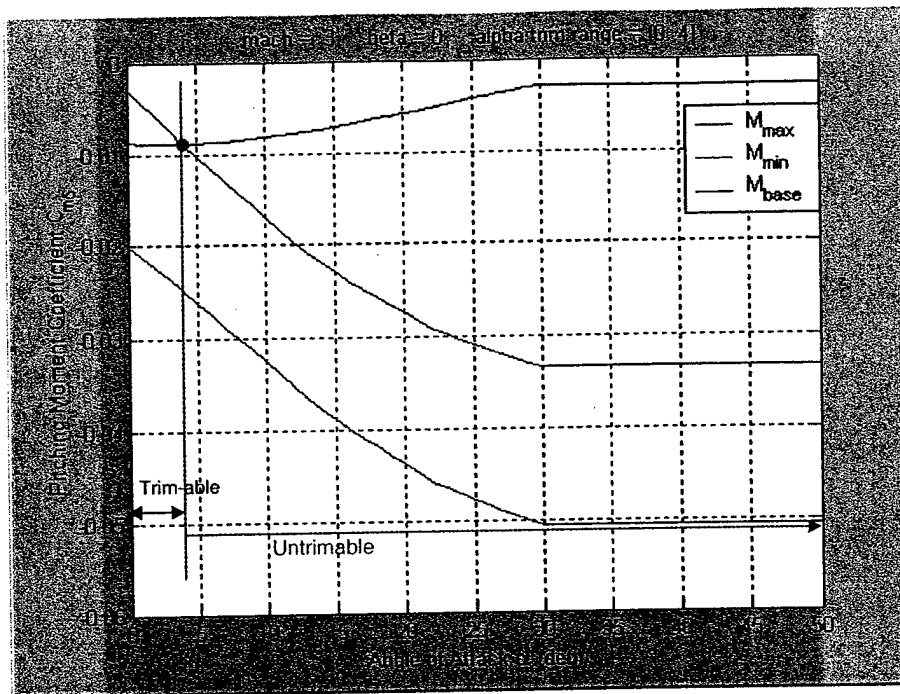


Figure 3: Determination of trimable angle of attack for a failed left-right flap (locked at 26°)

Figure 4 shows an example where the vehicle lost both body flaps effectiveness (known as floating flap failures). From the figure, one can see that the vehicle can be trimmed for the range of angle of attack ($\alpha=[13\ 50]$).

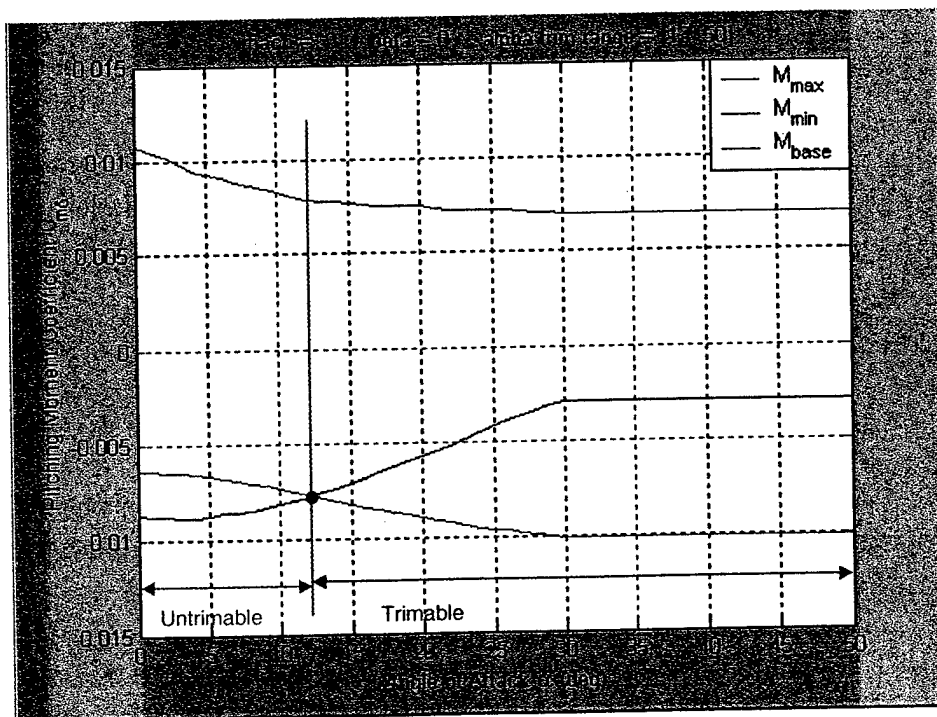


Figure 4: Determination of trimable angle of attack range for a failed right-left flap (floating at 0°)

The principle disadvantage of this algorithm is its application is limited to symmetric failures. The advantage of the second algorithm named "(NLAMS) Non Linear Attainable Moment Set", lies in its ability to compute a range of angle of attack (α) for all/any possible combination of effector failures. NLAMS is discussed next.

NLAMS Algorithm Design

The objective of NLAMS algorithm is to compute a range of attainable angle of attack (α) for a given flight condition and under any type of effector failure(s). Algorithm development concentrated on ways to extend/modify the AMS algorithm developed in reference [1]. Specific assumptions that were eliminated from this formulation are: the assumption of a linear relationship between the attainable moment set \vec{M} and the control effector positions \vec{U} , i.e., ($\vec{M} = B\vec{U}$) and the assumption of a prior trim able vehicle. The NLAMS algorithm uses the nonlinear aerodynamics instead of a linearized aerodynamic set and does not assume a trimable vehicle. Instead, NLAMS trims the vehicle's rolling and yawing moments first; then calculates the extremal values of the pitching moment that the effectors can generate while holding the rolling and yawing moments constant. Portions of Durham's AMS algorithm [1] were unchanged such as the boundary facet determination and the assumption of linearity was relaxed and replaced by the assumption that the moments were monotonic functions of deflection.

The NLAMS algorithm operation is summarized as follows:

1. For a given flight condition (Mach number and sideslip angle), effector displacement range, and the failure type,
2. Construct four vertices (edges of a facet) in the moment space (L, M, N) for each set of effectors where 2 effectors are allowed to vary at their minimum and maximum position limits while the rest of the effectors are locked at their minimum limits (to find 2 vertices) and maximum limits (to find the other 2 vertices). This effector position combination creates four vertices in the moment space that are connected together to form a linear surface (plane).
3. The linear surface is then evaluated to determine whether or not the surface is a boundary facet.
4. If the linear surface is indeed a boundary facet/plane, then four steps must be taken. First, a vector \vec{A} is constructed such that it trims the vehicle in the roll and yaw axes. That is, vector $\vec{A} = [-L_0, 0, -N_0]$, which insures a trimmed vehicle in the roll and yaw axes (refer to figure 4). Second, a least square fit plane is generated that best fits the four vertices. Third, a vector \vec{A} is extended parallel to the pitching moment axis M until vector \vec{A} intersects or pierces through the least square fit plane, i.e., choose $\vec{A} = [-L_0, \pm 1, -N_0]$ where large pitching moment coefficient values (+1 for positive moment and -1 for negative moment) are used. Finally, the point

of intersection between the boundary plane and the vector \bar{A} is computed. The distance from the point of intersection to the point $[-L_0, 0, -N_0]$ is the maximum (for +1) or minimum (for -1) attainable moment (C_m) as shown in Figure 4.

5. Since multiple boundary facets exist, the NLAMS algorithm has to determine the correct maximum and minimum pitching moments and the corresponding effector positions. This is accomplished by utilizing the nonlinear aerodynamic database and incrementing the angle of attack α over its range. For the range of angle of attack α , the nonlinear aerodynamic database is used to compute the base pitching moment $C_{m_0}(\alpha, \beta, mach)$, the maximum ($C_{m_{MAX}}$) and minimum ($C_{m_{Min}}$) pitching moments due to the effectors, and the minimum pitching moment due to the effectors. If the base pitching moment (C_{m_0}) lies between the minimum and maximum pitching moments (inside the AMS volume), then the vehicle can be trimmed in the pitch axis. The range of valid angle of attack α where the vehicle can be trimmed in the pitch axis is displayed on the plot.

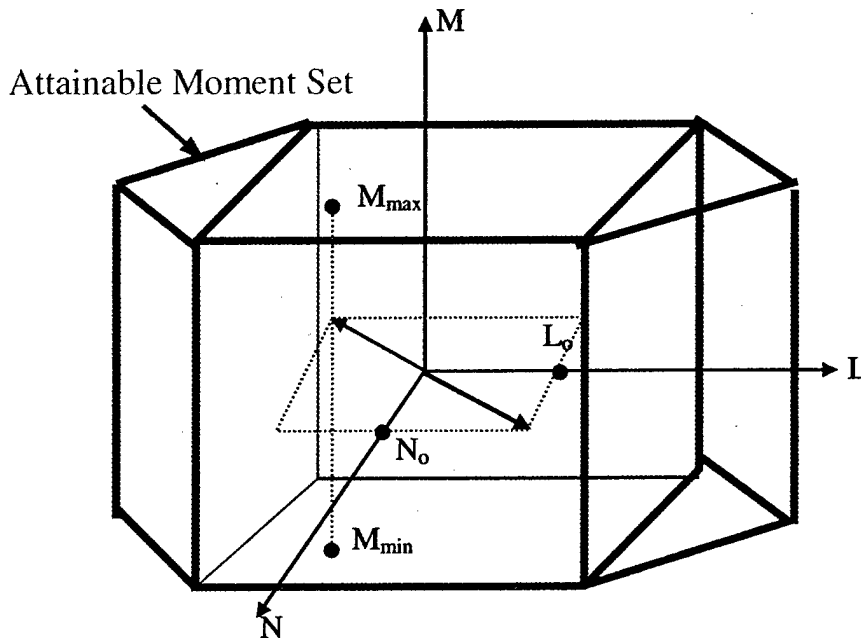


Figure 4: A 3-D figure showing the base moment vector

SIMULATION RESULTS

Four examples are presented in this section. The first three are to verify the test cases previously executed in the benchmark algorithm and the fourth example is a non-symmetric effector failure. The simulation results are tabulated in Table 1. All cases are for Mach = 3 and zero sideslip angle.

Effector failure case	Benchmark algorithm	NLAMS algorithm
1. Left flap failure (locked at 26°)	0.0000	0.0000
2. Right flap failure (locked at 26°)	0.0000	0.0000
3. Left flap failure (locked at 26°) and right flap failure (locked at 26°)	0.0000	0.0000
4. Left flap failure (locked at 26°) and right flap failure (locked at 26°)	0.0000	0.0000

Table 1

Figures 5-7 show graphically the range of angle of attack for the above first three cases. For case 3, it is interesting to conclude that this type of failure is uncontrollable for the given flight conditions. It is not possible to trim the vehicle if one or both of the flaps fail at their minimum displacement values as figure 7 shows.

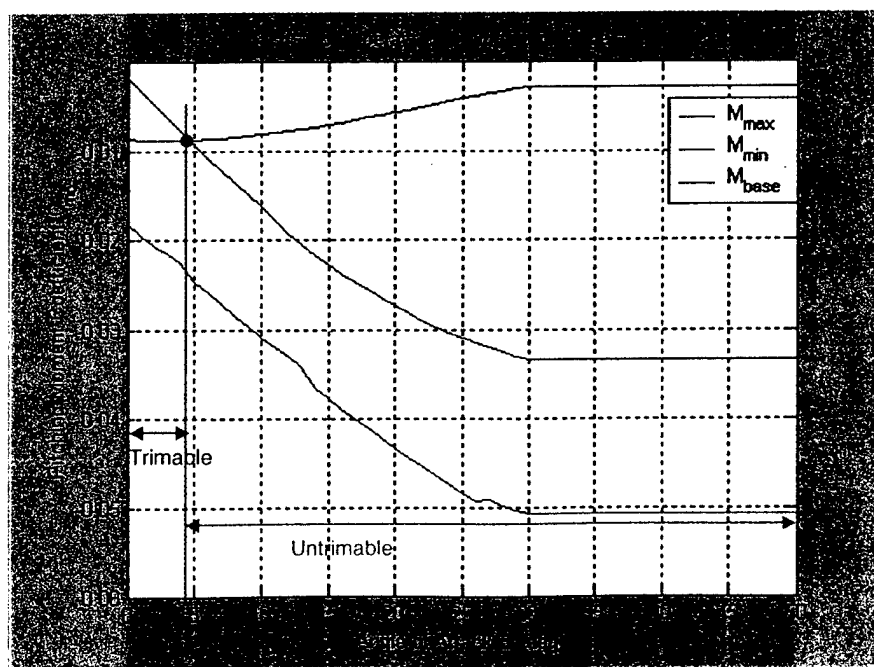


Figure 5: Determination of trimable angle of attack for failed left-right flaps (locked at 26°)

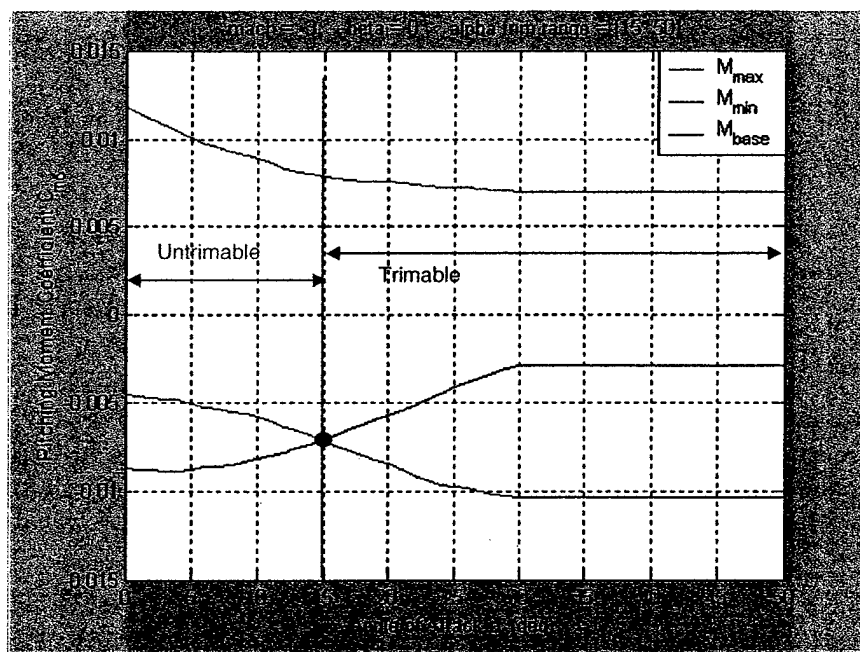


Figure 6: Determination of trimable angle of attack for failed left-right flaps (floating at 0°)

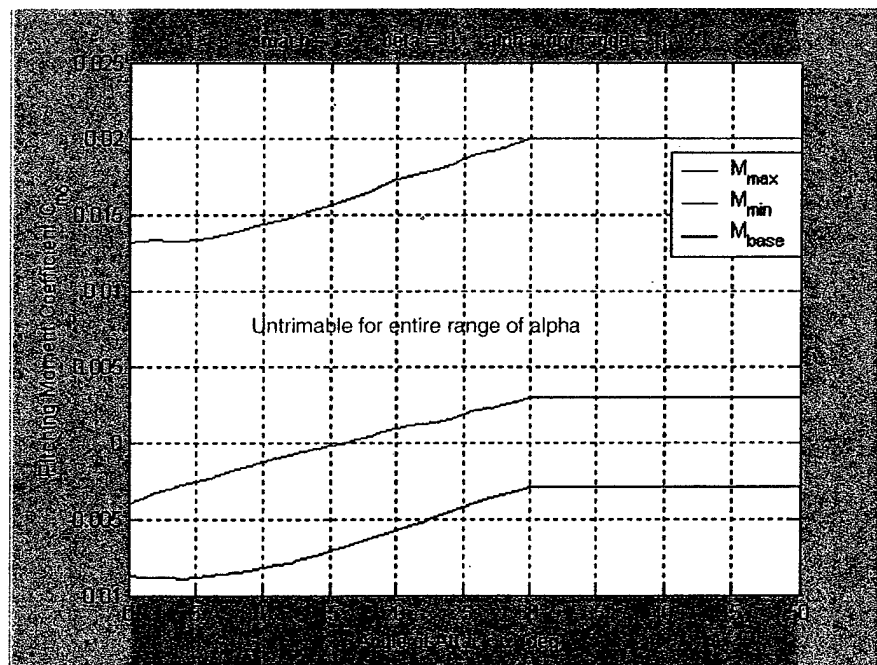


Figure 7: Determination of trim able angle of attack for failed left-right flaps (locked at -15°)

Note: Case 2 results vary slightly between the algorithms due to the assumption of a linear plane moment surface. That is, NLAMS calculation of the moment vector intersection with the pitching moment linear surface is an approximation of the nonlinear moment surface. The linear surface is constructed using the four

vertices/corners of the boundary facet. Figures 8 and 9 show this phenomenon in more detail.

Explanation of the linear versus nonlinear moment surface approximation:

- The current algorithm computes the vertices of boundary facets using the nonlinear aerodynamic database. The surface constructed by connecting the four vertices is assumed to be a plane (linear surface). However, the actual surface may be a nonlinear surface with convex or concave features. Thus, one needs to keep in mind that failures occurring at effector positions other than points where the vertices are computed will yield only an approximate value of the pitching moment. One possibility to minimize the error is to add the floating failure position (zero deflection) point to the minimum and maximum failures by creating an extra vertex in the middle of the facet (surface). The surface equation will be more representative of the nonlinear aerodynamics even though not an exact representation of the nonlinear aerodynamic surface. This phenomenon is shown in figures 8 and 9.

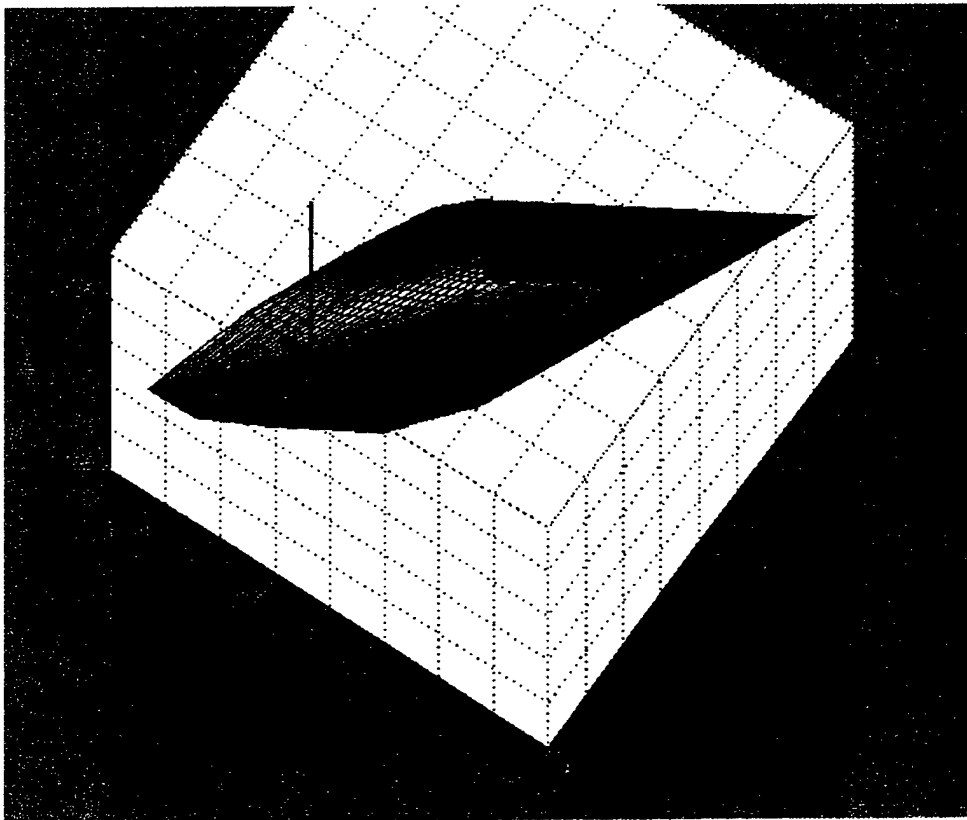


Figure 8: 3-D figure in moment space showing pitching moment intercept error

Figure 9 is a magnification of Figure 8 where the moment vector intersects the boundary surface. From Figure 9, the computed maximum attainable pitching moment intersects the linear surface at a different point than the nonlinear

surface. Thus, a pitching moment error is introduced that will change the range of the trim able angle of attack α . Three possible results can occur due to the surface discrepancies. 1) If the moment vector \vec{M} happens to intersect the linear plane and the nonlinear surface a facet vertex or where points on the nonlinear surface and facet plane are coincident, then one obtains an exact value for the range of α where the vehicle can be trimmed. 2) If the moment vector \vec{M} intersects the facet plane first, then one concludes that the range of α where the vehicle can be trimmed is conservative, i.e., the actual range of α is greater than the obtained one via NL-AMS. 3) If the moment vector \vec{M} happens to intersect the nonlinear surface first, then one concludes that the range of α where the vehicle can be trimmed is optimistic, i.e., the actual range of α is smaller than the obtained one via NL-AMS.

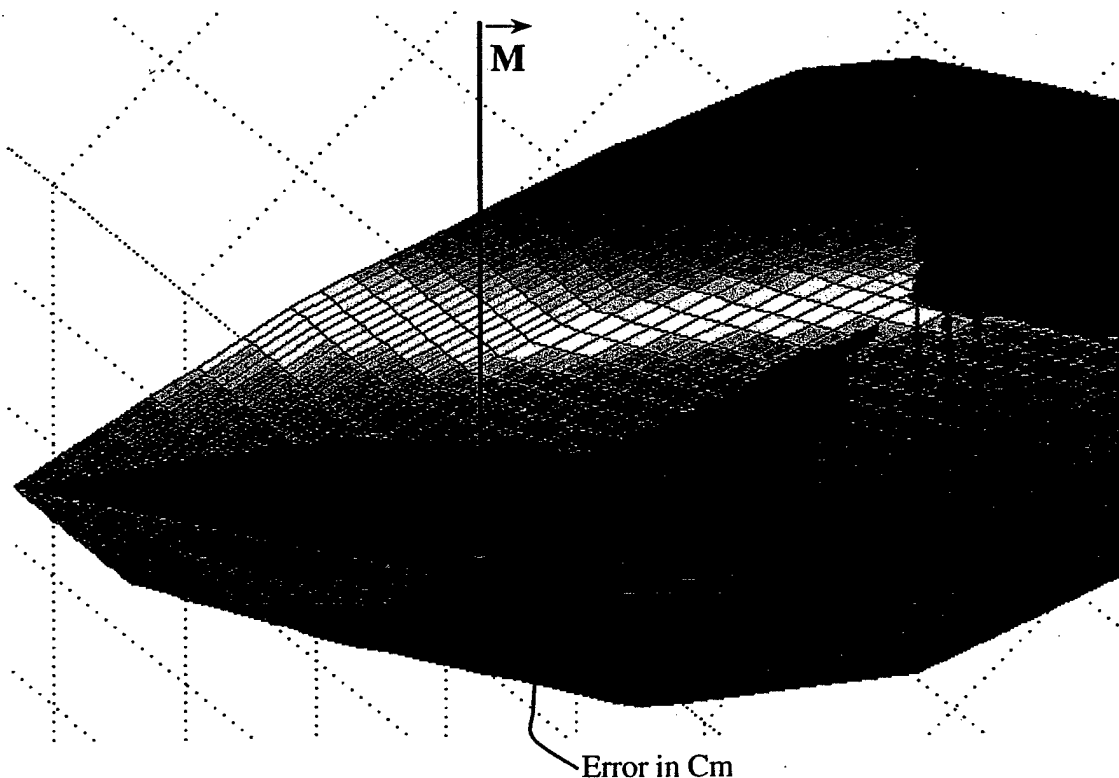


Figure 9: A detailed figure showing the pitching moment intercept error

CONCLUSIONS

This paper presented a method for computing the trimable range of angle of attack for air vehicles experiencing control effector failures. Types of failures considered include floating effectors that do not contribute to the vehicle aerodynamic forces and moments or locked effectors at a given position within the effector displacement range. The algorithm provides critical information to online trajectory generators or path planners for autonomous air vehicles. The NLAMS algorithm will be incorporated in an online footprint trajectory generator algorithm as part of a research project ongoing at Wright Patterson Air Force Base.

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